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Towards 400GBASE 4-lane Solution Using Direct Detection of MultiCAP Signal in 14 GHz Bandwidth per Lane

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Abstract: We report on an experimental demonstration of 102 Gbit/s transmission over a 15km single wavelength and polarization fiber link with 14GHz 3dB bandwidth. Novel multi-band CAP signaling allows for a 4-lane 400GBASE long reach solution.
OCIS codes: (060.2330) Fiber optics communications; (060.4080) Modulation

1. Introduction

Data center links operating at lane rates of 100 Gbit/s per wavelength are required in order to cope with future demands of bandwidth. In addition, there is an emerging need for increasing the reach up to 10 km, forcing 100 Gbit/s solutions to be robust to dispersion while keeping complexity low. By retaining a signal bandwidth of less than 28 GHz and using advanced multi-band, multi-level modulation format, we demonstrate experimentally a 15 km, 102 Gbit/s single wavelength and single polarization data link for extended reach client side.

Link capacities as high as 400 Gbit/s and even 1.6 Tbit/s are already projected as potential next steps. Current and upcoming standards for 100 Gbit/s, such as 100GBASE-SR10, 100GBASE-SR4, and 100GBASE-LR4 are based on using 10 lanes of 10 Gbit/s or 4 lanes at 25 Gbit/s each. Traditionally, the strategy for capacity upgrades has been to exploit the benefits of parallel optics and to rely on higher bandwidth availability for the electronic and optical components. However, this approach would require e.g. 16 lanes at 25 Gbit/s in order to achieve the 400 Gbit/s target, thereby making it challenging to meet 400 Gbit/s form-factor pluggable (e.g. CDFP2 and CDFP4) requirements on power consumption and footprint [1]. Therefore, it is crucial to develop other solutions for beyond 100 Gbit/s data links satisfying these industry requirements in terms of footprint, power consumption and cost efficiency.

Advanced modulation formats have gained increasing interest from research as well as industry as a method to reduce the number of lanes while increasing the total link capacity. Recent reported experiments include 112 Gbit/s half cycle - 16 level quadrature amplitude modulation (QAM) [2], and 100 Gbit/s, 25 Gbaud 4 level pulse amplitude modulation (PAM) [3]. Discrete multi tone modulation (DMT) has also recently been demonstrated to achieve 100 Gbit/s [4]. However, all mentioned approaches require either dual polarization or a wavelength division multiplexing (WDM) scheme to achieve the claimed bitrates, and thus doubles the number of lanes and light source-photo detector pairs required in the system.

This paper reports on a feasible solution for the possible upcoming 400 Gbit/s, 4 lane standards targeting 2 km to 10 km reach applications. The proposed scheme employs four 100 Gbit/s single wavelength, single polarization lanes. An experimental demonstration of a single lane with optical transmission over 15 km standard single mode fiber (SSMF) in the O-band has been carried out. A 102 Gbit/s signal using a novel multi-band carrierless amplitude phase modulation (MultiCAP) signal is successfully generated, transmitted and detected employing a link with an end-to-end 3 dB bandwidth of only 14 GHz. This experimental breakthrough is enabled by the combination of a novel signaling format and the use of digital signal processing techniques.

To the best of the authors' knowledge, this approach achieves the highest experimental reported bit rate using CAP modulation in a single wavelength, single polarization, and direct detection optical link. By the possible extension to 4 lanes, these results demonstrate the prospect for 400GBASE solutions with more than 10 km reach.

2. Principle of operation for multi-band CAP

Carrierless amplitude phase modulation (CAP) is a multidimensional and multi-level modulation scheme proposed in mid 70's by Falconer *et. al.* at Bell Labs [5]. CAP displays certain similarities to quadrature amplitude modulation (QAM) in its ability to transmit two streams of data in parallel. In contrast to QAM, however, CAP does not rely on a carrier, but uses filters with orthogonal waveforms to separate the different data streams. Although CAP, potentially, can support more than two dimensions, in its most fundamental form (2D-CAP), only two dimensions are used, and the two orthogonal waveforms are constructed by multiplying a square root raised cosine pulse with a sine and a cosine function respectively.
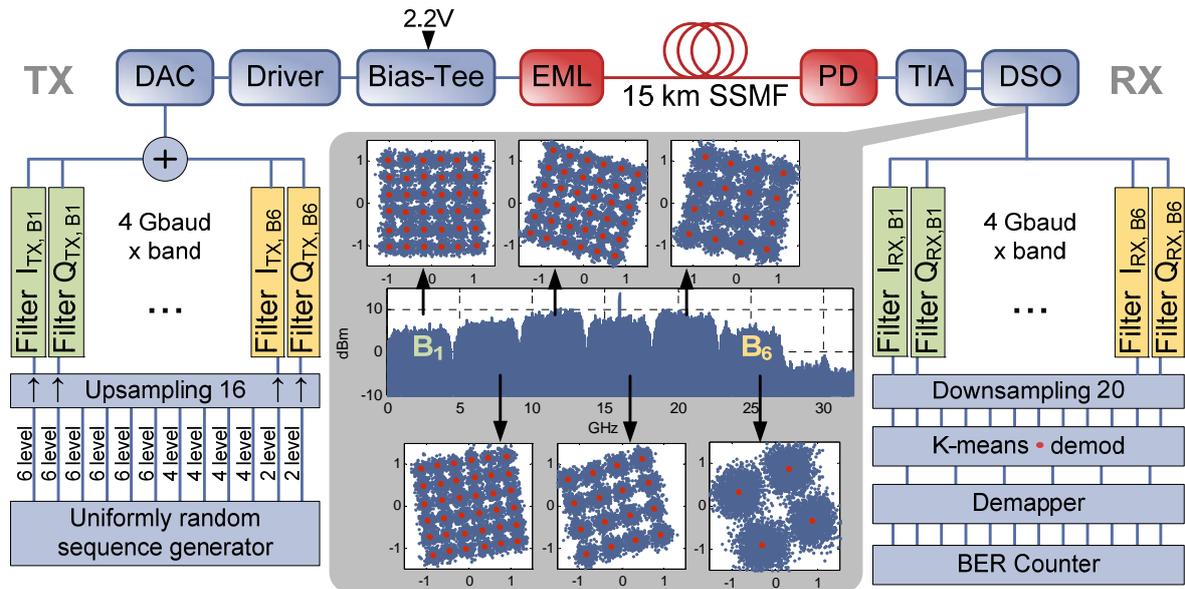
Fig. 1: Setup. Digital to analogue converter (DAC), externally modulated laser (EML), photodiode (PD), digital storage oscilloscope (DSO).

In this paper, we propose a novel, modified 2D-CAP modulation format termed MultiCAP, and employ it to achieve a bit rate of 102 Gbit/s. Instead of using a single 25-Gbaud, 16-level 2D-CAP signal to achieve 100 Gbit/s, 6 sub bands are constructed, each of them modulated at a symbol rate of 4 Gbaud. By breaking the signal into sub bands, the modulation order and signal power can be tailored to the signal to noise ratio (SNR) in each sub band. This effectively overcomes the greatest drawback of conventional CAP, namely the need of a flat frequency response of the channel. An additional advantage of MultiCAP in systems employing DSP for the signal generation is a relaxation of the requirement for the digital to analogue converter (DAC). For a conventional CAP signal, a minimum up sampling factor of three samples per symbol is required for acceptable performance, resulting in a total sampling rate of 75 GSa/s for a 100 Gbit/s 16 level CAP signal at 25 Gbaud. As the symbol rate in each sub band for a MultiCAP signal is much lower, a high up sampling factor can be used while the required sampling rate is kept at a minimum. In comparison to DMT, CAP is shown to offer advantages in SNR requirements and robustness to multipath interferences[6]. Additionally, (de)modulation can be implemented using electrical filters without the need for carrier recovery, frames or adaptive equalization. In our experimental demonstration, these features enable us to generate a 102 Gbit/s 6-band MultiCAP signal using a DAC with a sampling rate of 64 GSa/s, and transmit it over a channel with a 3 dB bandwidth as low as 14 GHz.

3. Experimental setup

The MultiCAP operation principle and the setup used in the experimental demonstration is illustrated in Fig. 1. The main building blocks are a transmitter comprising a DAC, a driver amplifier, a bias-tee and an externally modulated laser (EML); a 15 km SSMF link; and a receiver consisting of a PIN photodetector with a trans-impedance amplifier (TIA) and an 80 GSa/s digital storage oscilloscope. Signal generation and demodulation is performed off-line using Matlab.

For the signal generation, 12 uniformly distributed data sequences with a length of 16384 symbols are generated with modulation orders from 2 to 6 according to the desired modulation orders in the individual MultiCAP sub bands. The 12 symbol sequences are up sampled to 16 Sa/symbol and filtered by the 6 pairs of MultiCAP sub band transmitter filters. The filters are finite impulse response (FIR) filters with a length of 10 symbols each. The combined 102 Gbit/s MultiCAP signal is generated by simply adding the outputs of the 6 filter pairs. By adjusting the weights of each pair of filters, the non-flat frequency response of the channel is pre-compensated. The signal generation is performed in Matlab, and used to drive a 64 GSa/s DAC with an effective resolution of 5 bits.

The DAC output is amplified to a peak-to-peak voltage of 2 V and used to drive a 1293.55 nm integrated distributed feedback laser – electro absorption modulator (DFB-EAM) with the 3-dB bandwidth of 20 GHz. The signal from the DFB-EAM is propagated through a 15 km SSMF link with a total link loss of 7 dB. Launch power is 5 dBm. The optical spectrum back-to-back (B2B) and after transmission is shown in Fig. 3. The end-to-end channel frequency response is measured by performing a discrete frequency sweep with the DAC and shown in Fig. 4 along
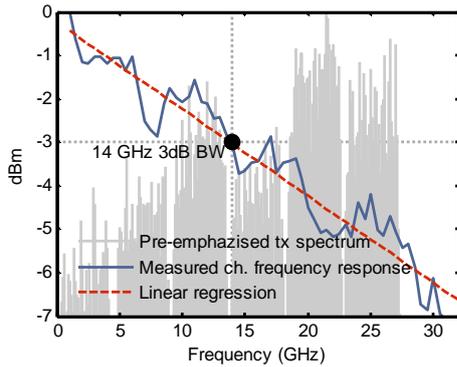
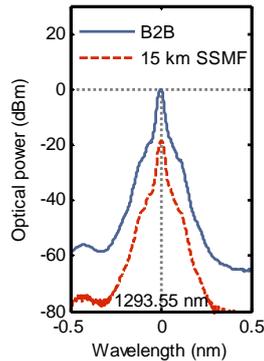Fig. 2: Frequency response pre-DAC signal spectrum
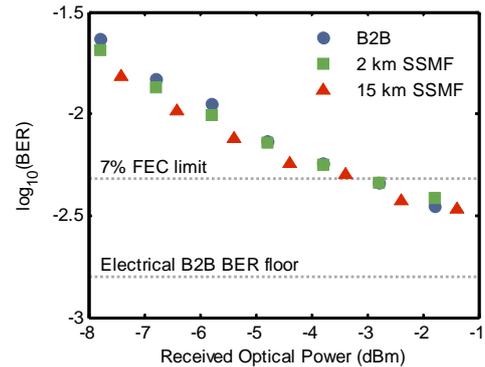

Fig. 3:Optical spectrums

Fig. 4: BER curves

with the spectrum of the pre-compensated 6-band MultiCAP signal. We can observe that the 3-dB bandwidth of the channel is 14 GHz, while the signal occupies a total bandwidth of 28 GHz.

After photodetection, the signal is sampled and stored by the DSO for off-line processing. The signal is demodulated by filtering with a time inverted version of the transmitter filters. After filtering, the signals are down sampled, and the two orthogonal components of the 6 bands can be obtained to construct the received constellation diagrams shown as inserts in Fig. 1 together with the received spectrum. Demodulation and compensation for constellation rotation and asymmetry caused by local non-flat in-band spectral response is performed employing the K-means algorithm [7].

4. Results

Fig. 2 shows the measured bit error ratio (BER) as a function of the received optical power B2B and after 2 km and 15 km SSMF transmission. Receiver sensitivity at the 7%-overhead forward error correction (FEC) limit of $4.8 \cdot 10^{-3}$ is -4.3 dBm in all cases, and no signal degradation or power penalty is observed from the transmission. Due to the limited effective resolution of the DAC [8], a BER floor of the electrical signal driving the EML is measured at $1.5 \cdot 10^{-3}$.

The advantages of the MultiCAP approach include ability for channel response pre-compensation, reduced DAC sampling rate requirements, and tailoring of the modulation order to the SNR of the individual sub bands is clearly observed, as these are exactly the features that enable the generation of the 102 Gbit/s signal using a 64 GSa/s DAC and transmitting it over an channel with an end-to-end 3 dB bandwidth of 14 GHz.

5. Conclusions

A novel approach named MultiCAP has been employed to demonstrate a 15 km optical link with a total bit rate of 102 Gbit/s using only a single wavelength and direct detection. In this reported experiment, assuming FEC encoding an effective bit rate of 95.36 Gbit/s is achieved. Despite the use of a high speed (64 GSa/s) DAC, the signal generation relies on the use of transversal filters in order to maintain a level of simplicity in the digital signal processing. By extending these results to four lanes, the prospects of 400 Gbit/s optical interconnect have been demonstrated for next generation client side data links.

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